Deformation of Alaskan Volcanoes, Measured by Satellite Radar Interferometry
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Summary

The purpose of this project was to determine the suitability of measuring active deformation of volcanoes in Alaska using Interferometric Synthetic Aperture Radar (InSAR) techniques. Work sponsored by this grant supported one graduate student (for almost 2 years) and one postdoc (for several months), and has resulted in two published peer-reviewed papers and a front-page article in EOS. An additional paper is in review and a fourth is in preparation. An additional paper in preparation was based in part on research supported by this grant and in part by a successor grant from NASA's Solid Earth Natural Hazards program. Over the course of this research, we documented measurable uplift of Trident volcano in the Katmai group, conducted a systematic study of the change in phase coherence over time on volcanic surfaces, and measured and modeled the spectacular 1.5 m deflation of Okmok caldera associated with its 1997 eruption. We also generated initial interferograms spanning the 1996 seismic swarm of Akutan volcano; however, during the period covered by this project we were not able to remove topography. That has been done under the subsequent funding and a paper is now in preparation.

This report summarizes work done under two separate contracts because both were based on the same proposal to NASA's ADRO program. The first year was funded out of a grant from NASA Headquarters and the second and third years out of a grant through Goddard. The work, however, was a continuous three year effort.

Lu, Z., R. Fatland, M. Wyss, S. Li, J. Eichelberger, K. Dean, and J. Freymueller, Deformation of New Trident Volcano detected by ERS-1 SAR Interferometry, *Geophys. Res. Lett.*, *24*, 695-698, 1997.

Lu, Z., and J. Freymueller, Synthetic aperture radar (SAR) interferometry coherence analysis over Katmai volcano group, Alaska, *J. Geophys. Res.*, *103*, 29,887-29,894, 1998.

Lu, Z., D. Mann, and J. Freymueller, Satellite radar interferometry measures deformation at Okmok volcano, EOS Trans. AGU, vol. 79 no. 39, 461-468, 1998.

Lu, Z., D. Mann, J. T. Freymueller, and D. Meyer, Synthetic Aperture Radar (SAR) Interferometry Observations of Okmok Volcano, Alaska 1. Radar Observations, *submitted to Journal of Geophysical Research.*

Mann, D., J. T. Freymueller, and Z. Lu, SAR Observations of Okmok Volcano, Alaska 2. Deformation associated with the 1997 eruption, in preparation, *to be submitted to Journal of Geophysical Research.*

Katmai Inflation

Using Interferometric Synthetic Aperture Radar (InSAR) techniques on SAR images for the Katmai group of volcanoes, Alaska, we detected a small area of uplift near the New Trident vent on Trident volcano. An area about 3 km by 3 km in size was uplifted by about 50-70 mm over a two year period from 1993-1995 (Figure 1). Phase coherence was lost outside of this area, so we cannot be sure if the area of uplift is confined to this area, although it cannot be too extensive since GPS measurements several km away did not detect any resolvable deformation [*Kleinman et al.*, 1996]. Based on the changes in phase over the area of coherence, and assuming a simple model of pressure change in a spherical point-source embedded in a uniform elastic half-space, we estimated the source depth to be in the range of 0.8 to 6.0 km. If we add the observation that no observable deformation occurred within the nearby GPS network, a source depth in the range 0.8-2.0 km is inferred. This location and depth corresponds to a zone of intense microseismicity ($M < 2$) [A. Jolly, personal communication, 1997].

Active uplift in this region was verified in the summer of 1997 by geological field observations. A geological team visiting the site found active fumaroles and clear evidence of a small dome-like uplift. Although these observations do not constrain the timing of the uplift, it is clear that this region has seen significant uplift, much more than the amount observed by InSAR, since the lava that lies on the surface was erupted in 1963.

Phase Coherence

We evaluated the phase coherence of 58 interferograms with time separations ranging from three days to three years. Rather than attempting to evaluate coherence over the entire image, we selected five specific areas where the surface material was known based on field geological experience. The target areas were selected prior to forming the interferograms. We computed a correlation coefficient for each site for each pair of images. The correlation coefficient measures the extent to which the radar signal is consistent from image to image. The interferometric SAR echoes will be correlated with each other if the backscattering characteristics remain unchanged between the two images. This kind of systematic study of phase coherence has not been done before, especially not for volcanic materials. Interferometric coherence is significant because: 1) it determines the precision of topographic or ground surface deformation maps made from an interferogram; 2) it could be a key channel for image classification for land and forest mapping; 3) it determines the feasibility of applying interferometric SAR techniques to geophysical studies; 4) it guides the planning of future SAR missions, by controlling how often a satellite must pass over a site to make future measurements.

We analyzed the interferograms constructed for the Katmai volcano group, Alaska. We selected five sites with typical volcanic surfaces: fresh lava, old weathered lava, ash with strong water re-working, ash with weaker water re-working, and stream deposits. We first investigated seasonal changes in coherence. We used a series of image pairs acquired at different times of year, each pair with a 35 day time interval between images. For all of the sites, we found that coherence is highest for images acquired between the middle of July and the end of September, and phase coherence decreases rapidly outside of this time interval. After the end of November, coherence was completely lost for images separated by 35 days, presumably because of continuous snow cover.

In general, fresh lava has the highest coherence, followed by either weathered lava or stream deposits (surprisingly, these seem to have higher coherence than weathered lava outside of the peak period). The sites where the surface material is ash deposited in 1912 show the poorest coherence at all times. Using images acquired exclusively during the peak of coherence in the summer, we studied the coherence as a function of the time separation between the images. We

applied a theoretical correction for the degradation of coherence with increasing baseline length to remove the effect of varying baseline separation. Over periods varying from 35 days to three years, we found that phase coherence for fresh lava and weathered lava decays more slowly than the other three sites. The decrease of coherence can be fit well by an exponential decay with time, with a time constant of order of years. For the best surface materials, we find acceptable phase coherence for image pairs separated by as much as three years. However, for the worst materials phase coherence is degraded within a matter of months to a point where meaningful signals are unlikely to be obtained (Figure 2).

These results suggest that long-term monitoring of volcanoes that are subject to seasonal snow cover is feasible, although phase coherence is not likely to be maintained over a broad area unless the surface conditions are ideal. In order to maintain coherence over a broad area, a satellite must make a usable pass over the volcano at least every two or three months in the summer, and every two or three weeks in spring and fall, and every two or three days in the winter.

Okmok Eruption

Using ERS-1 and ERS-2 synthetic aperture radar (SAR) interferometry, we studied surface deformation before, during, and after the April 1997 eruption of Okmok volcano, Alaska. We first derived an accurate digital elevation model (DEM) using a tandem ERS-1/ERS-2 image pair and the pre-existing USGS DEM. We then quantitatively assessed the atmospheric delay anomalies in the interferograms. Atmospheric delay anomalies in some of the interferograms were significant, although almost always smaller than 1-2 fringes in magnitude, and repeat observations are important to confidently interpret small geophysical signals related to volcanic activities. Finally, using several interferograms, we analyzed the pre-eruptive inflation, co-eruptive deflation, and post-eruptive inflation, and confirmed the observations using independent image pairs.

We measured more than 140 cm of subsidence associated with the 1997 eruption of Okmok volcano (Figure 3). This subsidence occurred between 16 months prior to the eruption and 6 months after the eruption, was preceded by about 18 cm of uplift between 1992 and 1995 centered in the same location, and was followed by about 10 cm of uplift between September 1997 and 1998. The best fitting model suggests the magma reservoir resided at 2.7 km depth beneath the center of the caldera, which was about 5 km from the eruptive vent. We estimated a lower bound to the volume of the erupted material to be 0.048 km^3, and the average thickness of the erupted lava is about 6.4 m. By studying changes in interferometric coherence, we found out the newly erupted lava lost all radar coherence for 5-17 months after the eruption. The loss of coherence suggests changes in the surface scattering characteristics and was probably related to cooling and compaction processes

We have continued to use these interferograms to test methods of inverting InSAR data for deformation models. Our initial inversions used a series of linear profiles extracted from the interferogram as the input data. We found that the results of these inversions were actually quite robust, even though only a fraction of the data were used. We have upgraded our programs so that we can invert the data from discontinuous regions in a single inversion, without having to assume that we can maintain phase coherence between the regions. This augmentation is significant because interferograms for volcanic sources often have several discontinuous regions of coherence surrounded by incoherent regions that prevent phase unwrapping between regions. We have also experimented with inversions of the unwrapped interferograms directly. Inversion of unwrapped interferograms is inherently non-linear since the residuals are modulo 2π, and these inversions can be hampered by the presence of multiple local minima. However, in several cases we were able to recover best-fitting models that were in good agreement with the wrapped interferograms, as long as we could start from a reasonable starting model. This suggests that the technique may be useful once further development is done.

Akutan Seismic Swarm

Akutan volcano, situated in the west-central part of Akutan Island in the east Aleutian Islands, was struck by an intense earthquake swarm on March 10-14, 1996. The largest event in the swarm was a magnitude 5.1 on March 10, and in the first days of the swarm as many as 3000 earthquakes were felt per day. Most of the recorded earthquakes were volcano-tectonic events located to the east of the summit. Alaska Volcano Observatory (AVO) scientists observed fresh northwest-southeast trending en-echelon cracks on both the northwest and southeast flanks of the volcano. The cracks are up to 1 m wide. They are very fresh and are presumed to have formed concurrently with the earthquake swarm. An eight station Global Positioning System (GPS) network was measured with support from AVO in July and August 1996, concurrently with the installation of a permanent seismic monitoring network.

We measured the ground surface deformation associated with the March 1996 earthquake swarm and ground surface cracking (Figure 4). However, this interferogram includes the effect of topography since a suitable DEM is not available. Nevertheless, a comparison of this interferogram with another showing only topography suggests that significant deformation occurred. Zhong Lu has continued to work on this problem after the expiration of this grant, and has now obtained some interferograms with topography removed that he has modeled along with scientists from the U.S. Geological Survey.

Figure 1. Motion-only interferogram for New Trident vent constructed using ERS-1 images. The area shown is about 3 km by 3 km. One fringe (three color band of red-green-blue) in the interferogram represents 28.3 mm difference in distance from satellite antenna to ground surface between two observations during 1993 and 1995. The observed 70 to 90 mm uplift at New Trident vent over two years can be explained by shallow inflation source located within 2 km of the surface. This inflation source could be a small magma body. Inflation could be due to the arrival of new magma near the surface, or expansion of gases.

Figure 2. Degradation of phase coherence, measured by the correlation coefficient between the two images, over time for five different surface materials. The correlation coefficients are corrected for the decorrelation due to baseline length, so the corrected correlation coefficients all refer to an ideal zero baseline separation. The correlation coefficient for a 200 meter baseline separation, for example, would be about 80% of the value shown. Based on our experience with Katmai interferograms, a correlation coefficient of about 0.3 or higher is required for an useful interferogram.

Figure 3. Deformation interferogram spanning 9 October 1995 to 9 September 1997, which brackets the February 1997 eruption of Okmok volcano. Each fringe represents a 2.83-cm deformation along the satellite look direction.

Figure 4. Interferogram for Akutan volcano, including the effect of topography as well as the deformation associated with the 1996 seismic swarm.

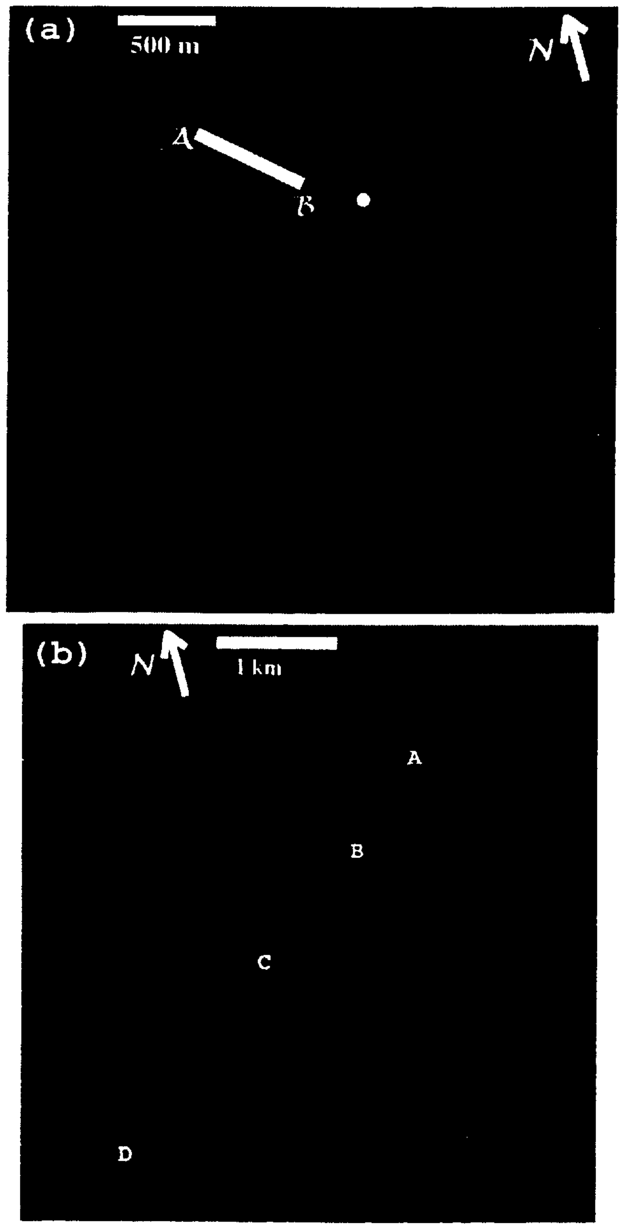
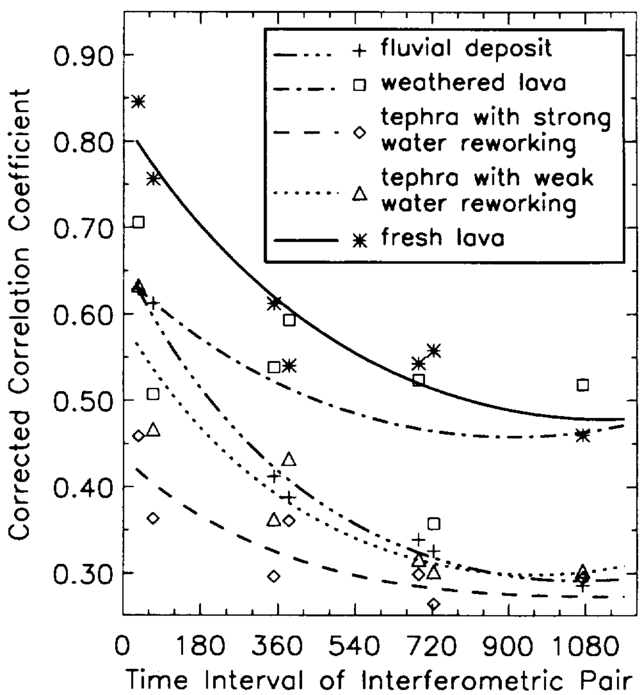


Figure 1



fluvial deposit
weathered lava
tephra with strong water reworking
tephra with weak water reworking
fresh lava
Corrected Correlation Coefficient
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0
180
360
540
720
900
1080
Time Interval of Interferometric Pair

Figure 2

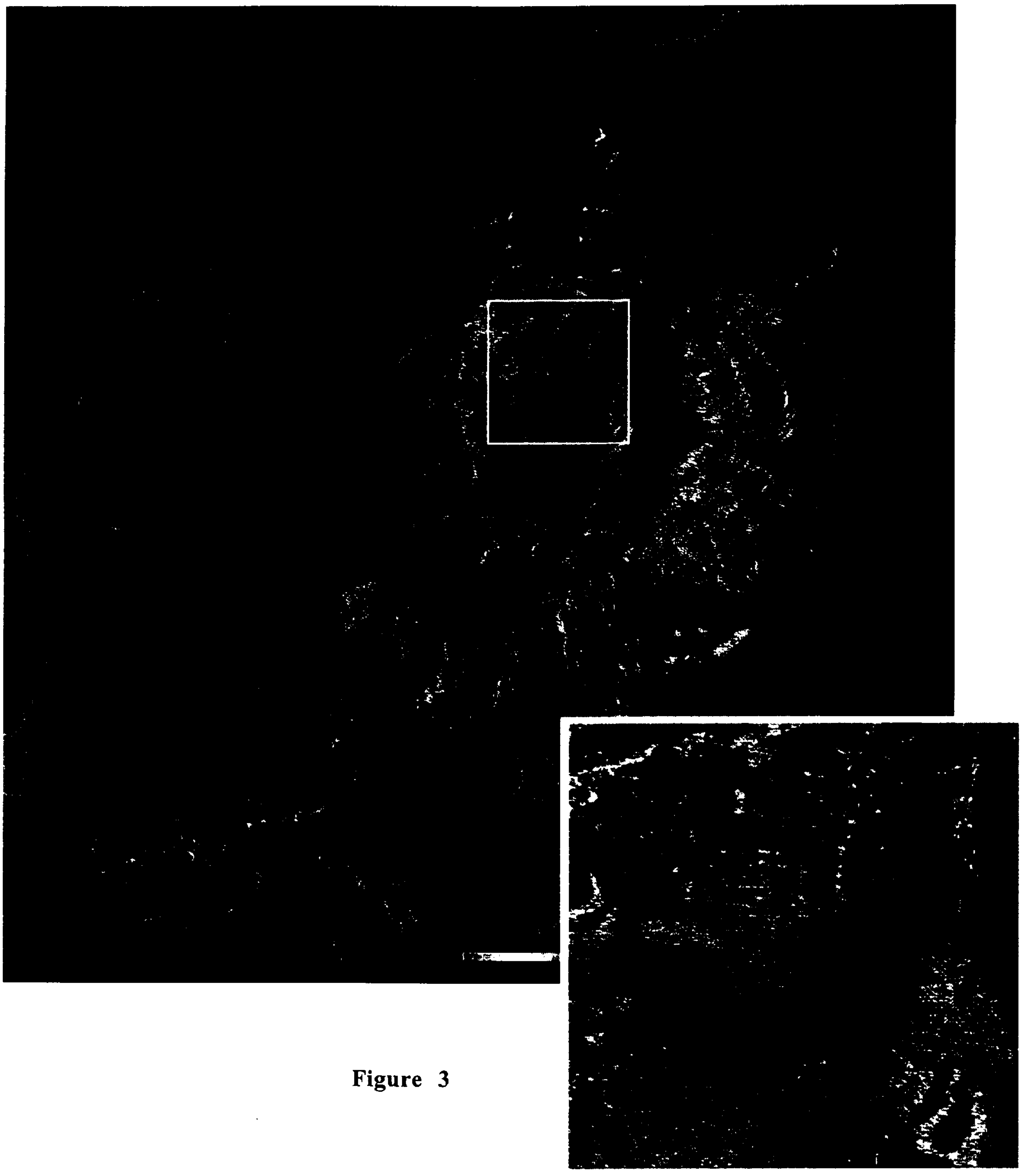


Figure 3

Figure 4